Exploring ice formation and migration in frozen soils

Yanxin Mao[1], Enrique Romero[1 *], Guido Musso[2], Antonio Gens[1]

[1] Universitat Politècnica de Catalunya, Barcelona, Spain
[2] Politecnico di Torino, Torino, Italy
* Enrique.romero-morales@upc.edu

Abstract

A relatively simple method is proposed to indirectly determine the unfrozen liquid saturation at different temperatures, porosity and initial degrees of saturation. The method relies on the bulk electrical conductivity EC of a compacted soil, which is compared to the electrical conductivity of the pore liquid. The method was applied to interpret the progressive freezing of a cylindrical sample that was exposed to very low temperatures at its central axis. The process was monitored with an electrical resistivity tomography cell. Reconstructed maps of EC were interpreted with the proposed model to determine the unfrozen liquid saturation at different elapsed times.

Temperature effects on the electrical conductivity of soils

In soils, temperature decrease leads to a concurrent decrease of electrical conductivity. This occurs because of two phenomena. For temperatures above freezing, the mobility of the ions dissolved in the liquid phase depends, quite linearly, on temperature. For temperatures below freezing, ice formation reduces the fraction of liquid water, which is the main carrier of electrical current, since the electrical conductivity of the solid phase is, as a first approximation, negligible in soils with moderate specific surface. These two effects were separately studied to allow using EC to determine the ice content of laboratory samples. First, the relationship between temperature and EC of samples was derived for different porosity and initial degrees of saturation. Then, the monitoring of the evolution of EC of a cylindrical sample during a transient freezing process was done through electric resistivity tomography ERT, obtaining EC maps at different time instants that were converted into maps of unfrozen water saturation.

Material and methods

Barcelona clayey silt, compacted at different initial porosity and degrees of saturation, was used in the experiments. The soil presented a liquid limit of 30%, a plastic limit of 19% and 16% of clay size fraction ≤2 µm (Mao 2018). A 5% NaCl solution was used as pore liquid to allow for a good characterization of the effects of temperature on EC, The experimental set up is presented in Fig. 1 (Mao 2018, Comina et al. 2008). Samples installed in a small cylindrical cell were immersed in a cooling bath (- 15 °C) while measuring temperature and EC (Fig. 1a). Transient experiments were also conducted in cylindrical samples, on which a temperature of -15°C was applied at its central axis and adiabatic conditions were imposed at the external boundaries. The bulk EC of the soil without phase change σ_T^* was interpreted with a modified Archie's law (Archie 1942):

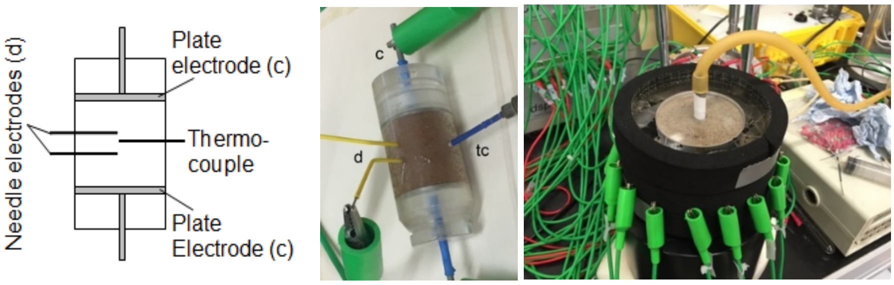
$$\sigma_T^* = \sigma_T\left(T\right) n^p S_{ri}^q \ ; \ \sigma_T\left(T\right) = 1.32T + 42.45 \ ; \ p = 1.85 \text{ and } q = 2.08$$

where $\sigma_T(T)$ is the EC of pore liquid [dS/m] at given temperature T [°C]; n is porosity; S_{ri} is the initial degree of saturation; p and q are exponents accounting for structure and tortuosity of the medium. Therefore, the unfrozen water saturation in a partially saturated frozen soil S_l could be evaluated as a function of the measured bulk EC of the soil σ_m (Mao et al. 2018):

$$S_l = S_{ri}\frac{\sigma_m}{\sigma_T^*} = \frac{\sigma_m}{\sigma_T\left(T\right)} n^{-p} S_{ri}^{1-q} \ ; \quad S_l = \frac{\sigma_m}{1.32T + 42.45} n^{-1.85} S_{ri}^{-1.08}$$

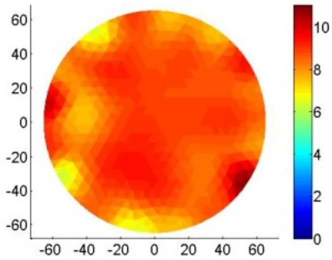
Experimental results

Homogeneous samples, having different initial porosity and degrees of saturation, were used to calibrate the above model parameters using the experimental cells of Fig. 1a and 1b (Mao et al. 2018). Two EC images obtained through ERT (sample 120 mm in diameter) at different elapsed times of a saturated sample (with porosity n=0.26) are plotted in Fig. 2a. The corresponding reconstructed images of unfrozen water saturation, evaluated by using the calibrated model, are presented in Fig. 2b.

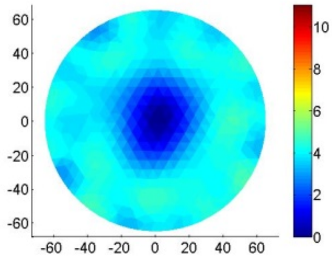


(a) (b) (c)

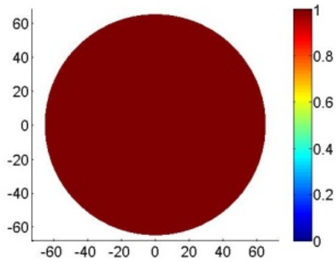
Fig. 1: (a) Schematic and (b) experimental setup of small cell for measuring EC of soils; (c) ERT cell.



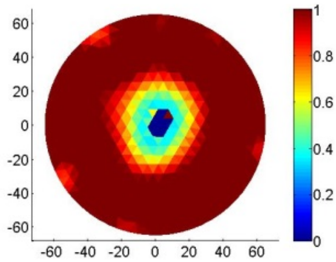
(a) t=0



(a) t=240 min



(b) t=0



(b) t=240 min

Fig. 2: (a) 2D ERT images of saturated sample (120 mm in diameter) during a freezing path: (left) EC at t=0 [dS/m]; (right) EC at t=240 min [dS/m]. (b) Reconstructed images of unfrozen liquid saturation: (left) t=0; (right) t=240 min.

Conclusions

The electrical conductivity of soils is shown to depend on the unfrozen liquid saturation and temperature, and the phenomenological laws that describe this dependence can be effectively calibrated by simple laboratory experiments. After proper calibration, ERT reconstructions can be used to infer the evolution of unfrozen liquid saturation in clayey silt samples undergoing transient freezing processes. The experience collected suggests that electrical methods can be a viable tool for the laboratory study of the physical processes related to freezing and thawing, and possibly also for in situ monitoring of engineering works where freezing is adopted to support construction operations.

Acknowledgements

The first author acknowledges the financial support from China Scholarship Council (CSC).

References

Archie G E (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME 146(01): 54-62

Comina C, Foti S, Musso G, Romero E (2008) EIT Oedometer: an advanced cell to monitor spatial and time variability in soil with electrical and seismic measurements. Geotechnical Testing Journal 31(5), 404-412. doi: 10.1520/GTJ101367

Mao Y (2018) Study of ice content and hydro-mechanical behaviour of frozen soils. PhD dissertation, Universitat Politècnica de Catalunya, Spain

Mao Y, Romero E, Gens A (2018). Ice formation in unsaturated frozen soils. 7th Int. Conf. on Unsaturated Soils, Hong Kong, August 3-5, 2018 (accepted)